Quantum Information Processing with Trapped Ions at Michigan

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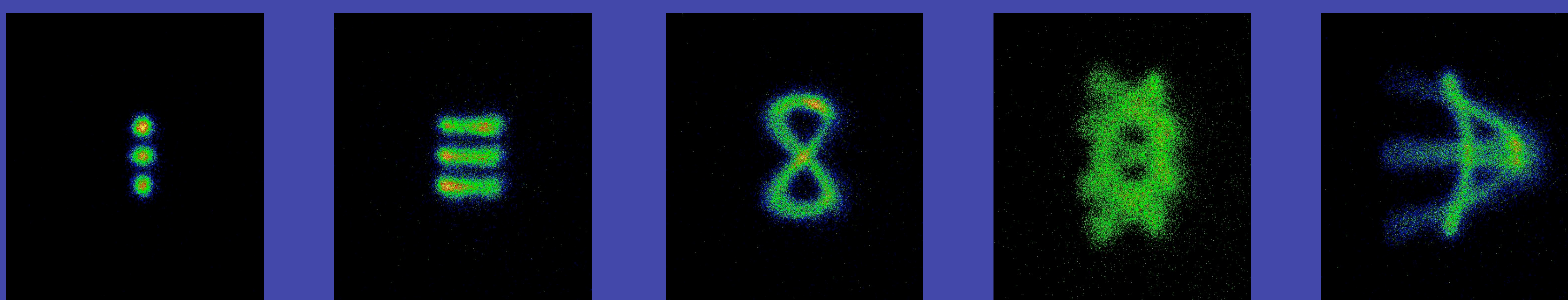
Outline

- Introduction: ion trapping, types of RF ion trap, ions as qubits...
- Research directions:
  - high-fidelity gates with Cd^+ ions
  - microtraps and trap arrays
  - high-power laser pulses on ions
- Conclusions and outlook



Michigan Ion Trap group

PI: Chris Monroe

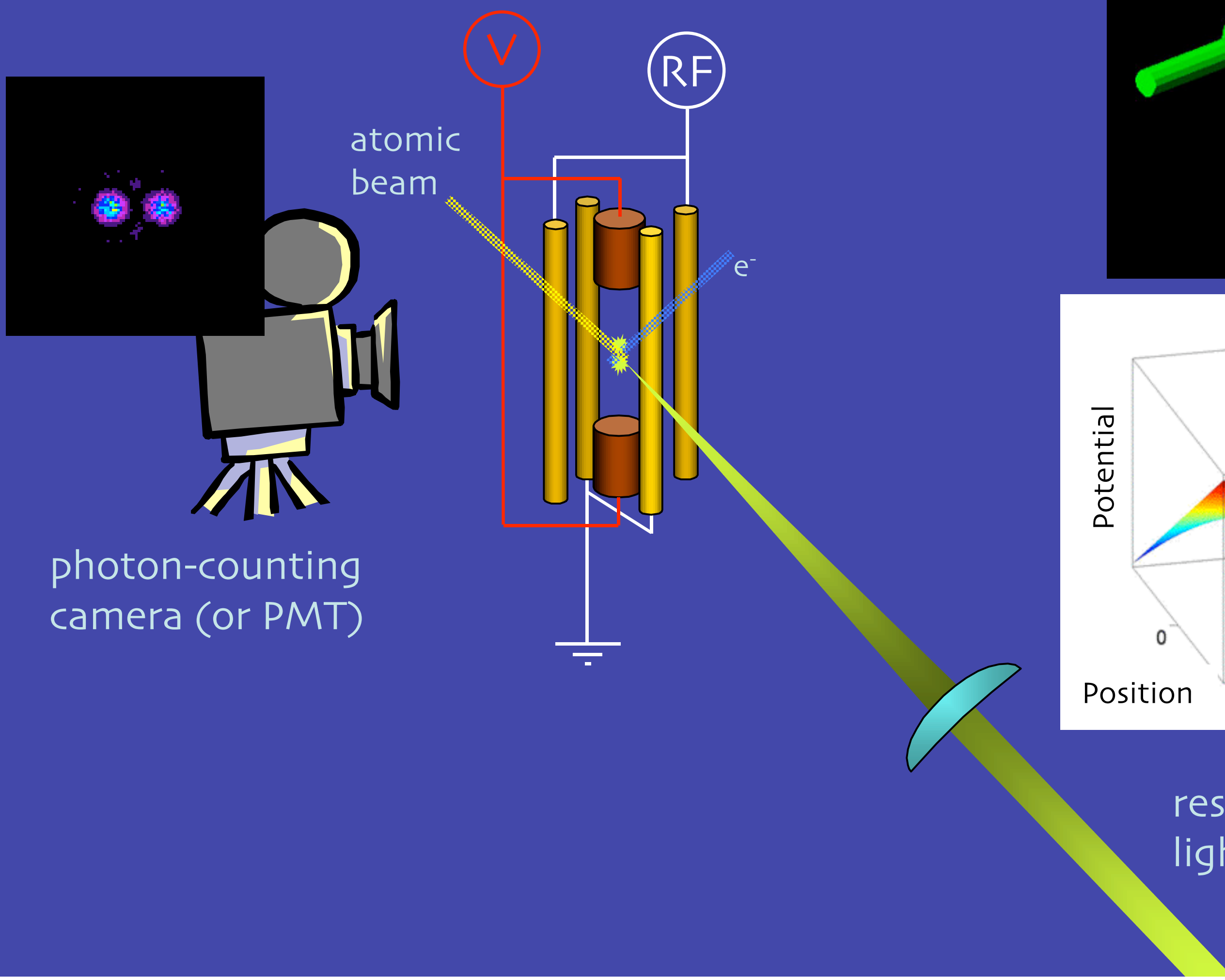
Faculty: Jens Zorn

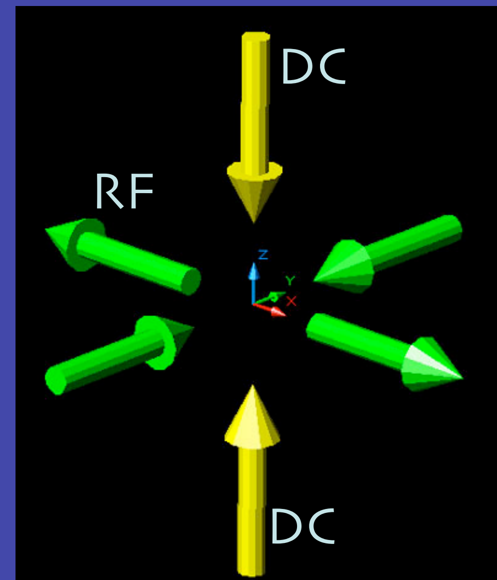
Postdocs: Boris Blinov, Paul Haljan, Winfried Hensinger, Chitra Rangan

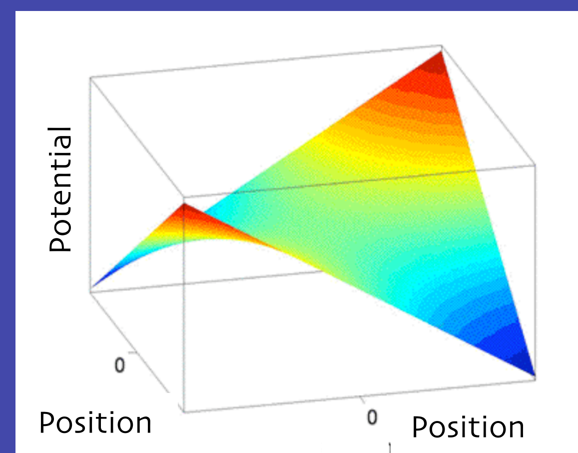
Graduate students: Kathy-Anne Brickman, Louis Deslauriers, Patty Lee, Martin Madsen, David Moehring, and Daniel Stick

Undergraduate students: David Hucul, Rudy Kohn Jr., Russell Miller (ret.)

RF (Paul) ion trap



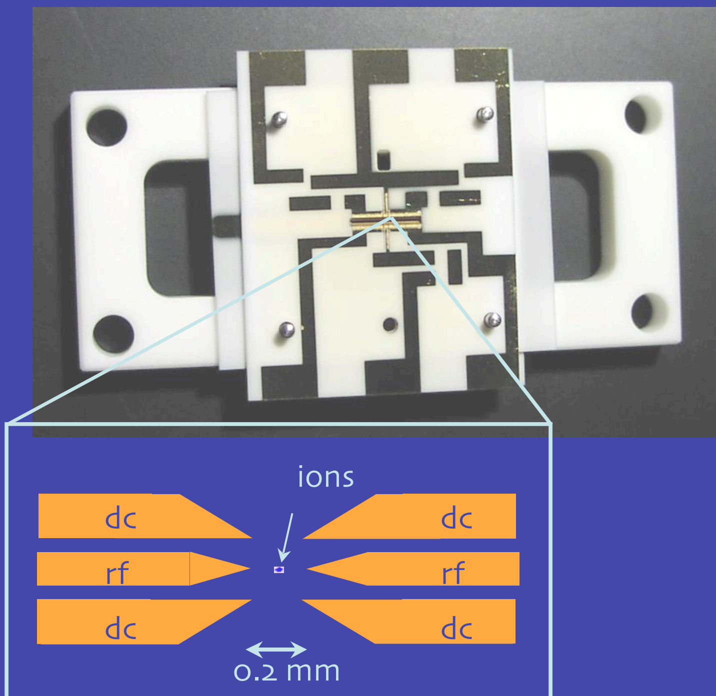




Practical trap designs

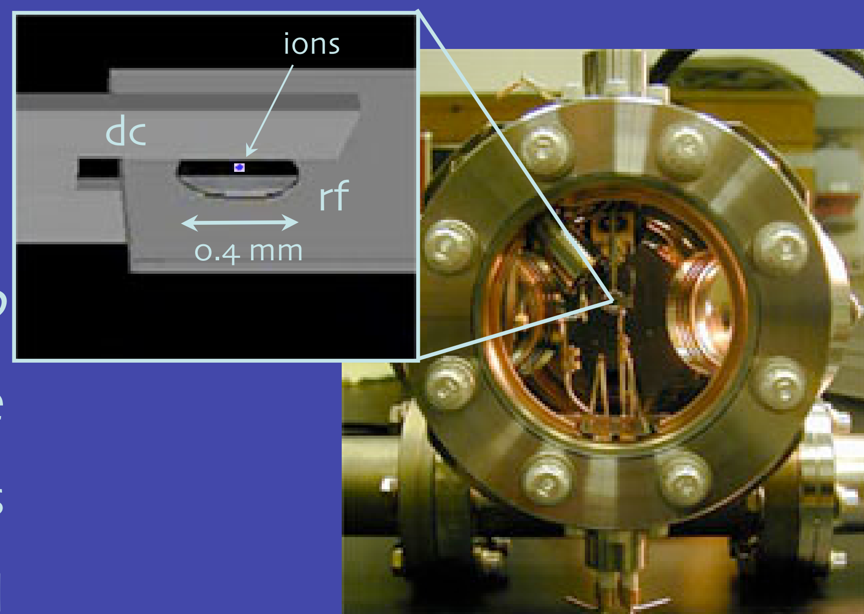
3-layer lithographic linear trap

- RF nodal line (ion string)
- static voltage compensation electrodes
- 200 micron size (strong confinement)
- 3-layer geometry allows multiplexing, T-junctions, etc.

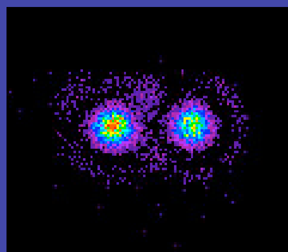


Ring-and-fork quadrupole trap

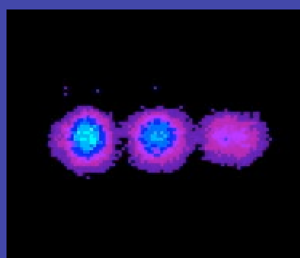
- easy to build and operate
- good optical access
- trapping few ions near RF null



Trapped ions - as seen on TV



Two Cd^+ ions in a 3 MHz trap (~2 □m separation)



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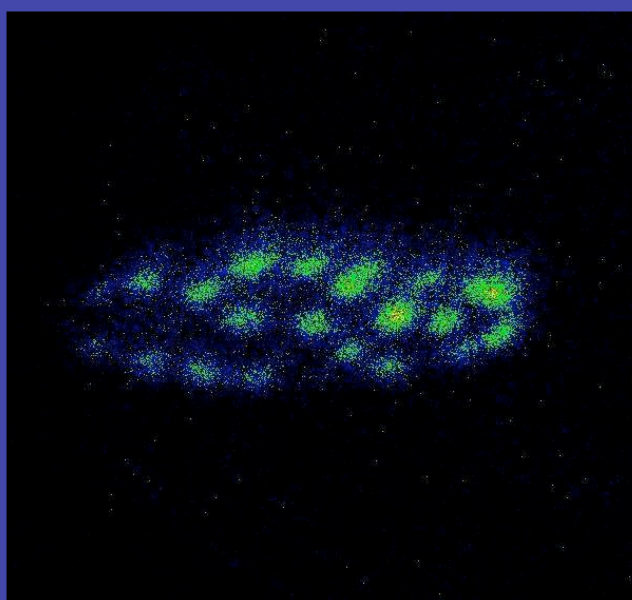
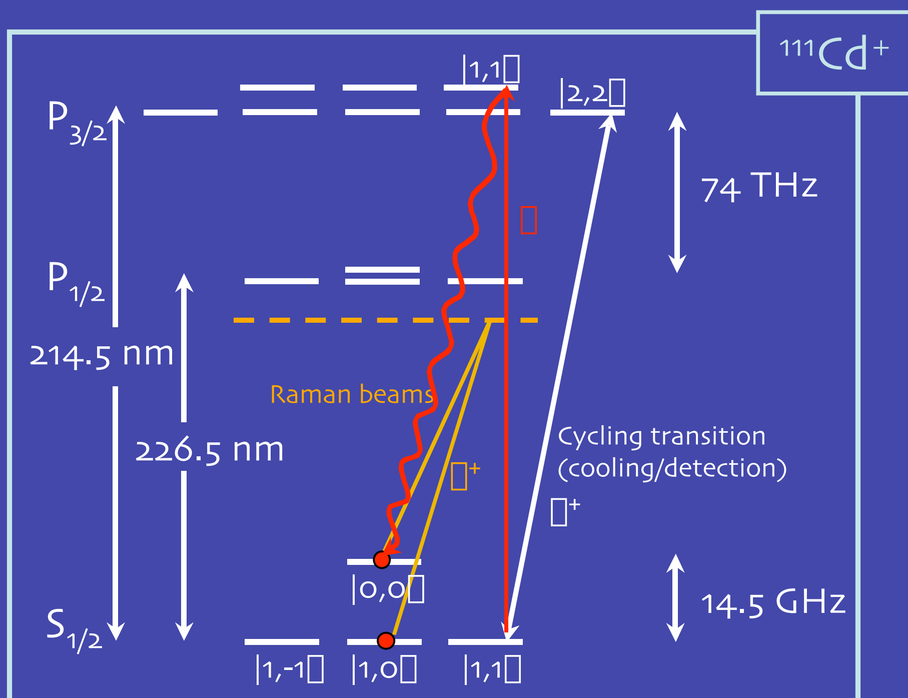


Multiple-ion helical crystal (Cd^+ and possible impurity). Weak trap (~0.5 MHz, 6□m separation)

Trapped ions as qubits

- Strong confinement in an RF trap (1-10 MHz) - qubits well localized
- Long-lived atomic levels form extremely stable qubit
- Efficient qubit state detection by fast cycling transitions
- Initial state preparation by optical pumping with near-perfect efficiency
- Qubit rotations using microwaves or lasers
- Quantum logic gates via strong Coulomb interaction between ions
- Coupling to “flying qubits” (photons) using cavity QED
- Sympathetic cooling to reduce decoherence



Entanglement of trapped ions

- Coulomb-force based entanglement:

  - Cirac-Zoller CNOT gate (1995) - spin-state coupled to phonons of ion crystal vibrations

  - Mølmer-Sørensen gate (1999) - spin-state coupled to phonons of ion crystal vibrations, but motional states never populated

  - Cirac-Zoller "push" gate (2000) - phase gate through direct Coulomb repulsion of neighboring ions

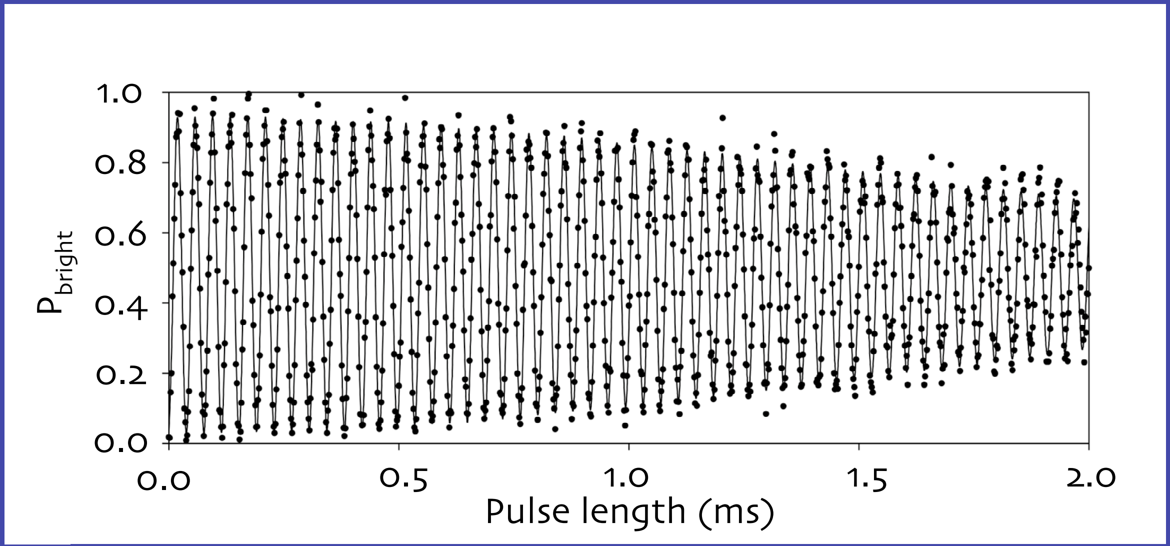
  - Cirac-Zoller ultrafast gate (2003) - series of fast π-pulses generate phase gate (arXiv:quant-ph/0306006)

- Photon-mediated entanglement:

  - trapped ion-cavity QED merger – spin-state mapped onto field state inside the high-finesse optical cavity

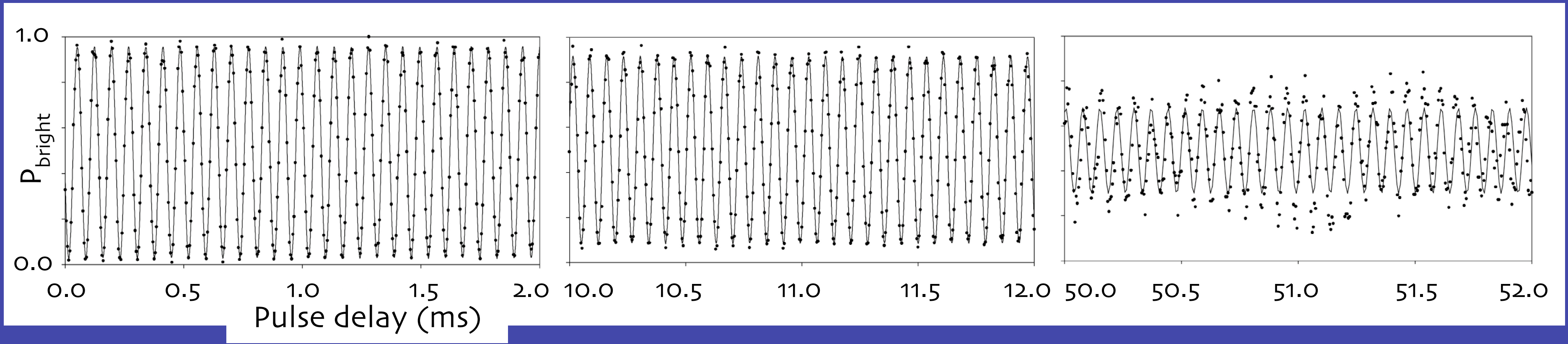
Towards high-fidelity quantum logic gates with Cd ions

Paul Haljan
Kathy-Anne Brickman
Louis Deslauriers
Patty Lee

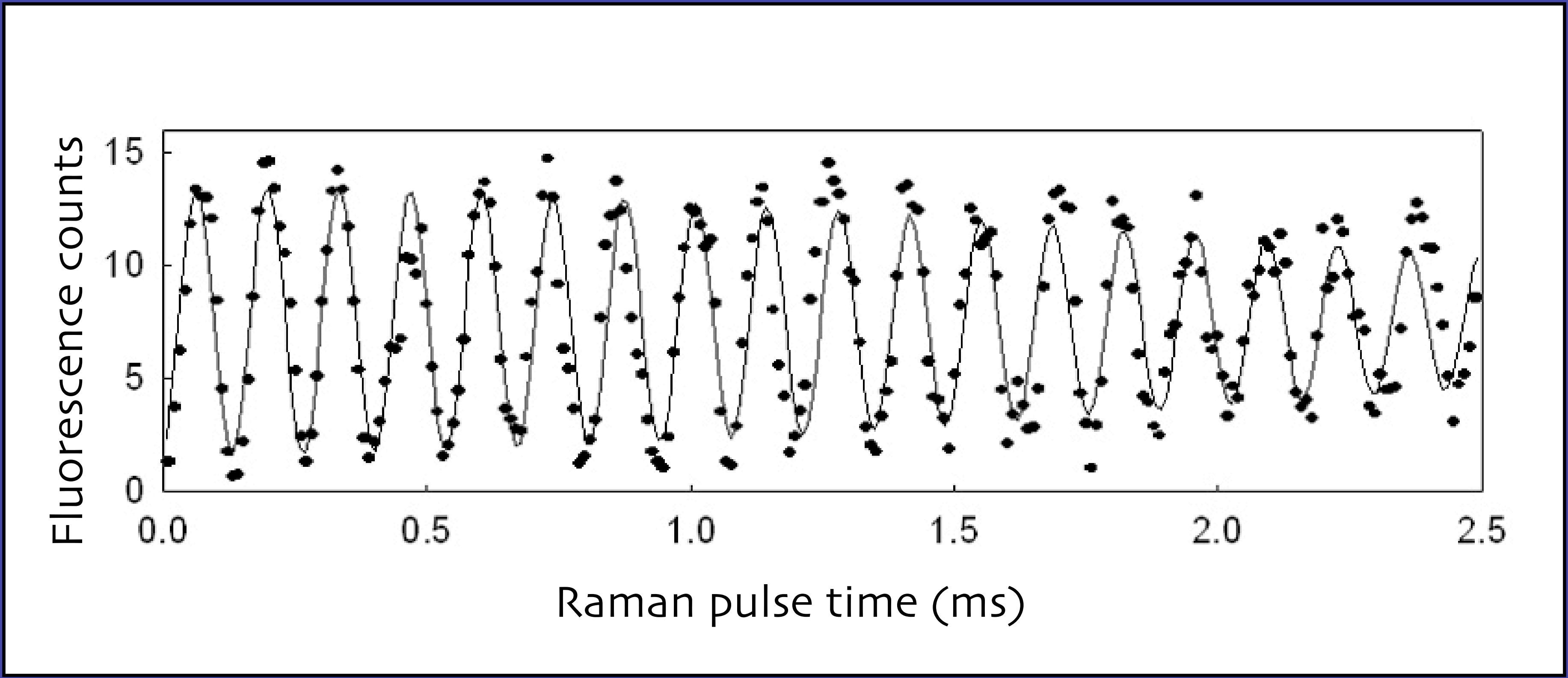


Rabi flopping between the hyperfine levels of a single $^{111}Cd^{+}$ ion using microwaves

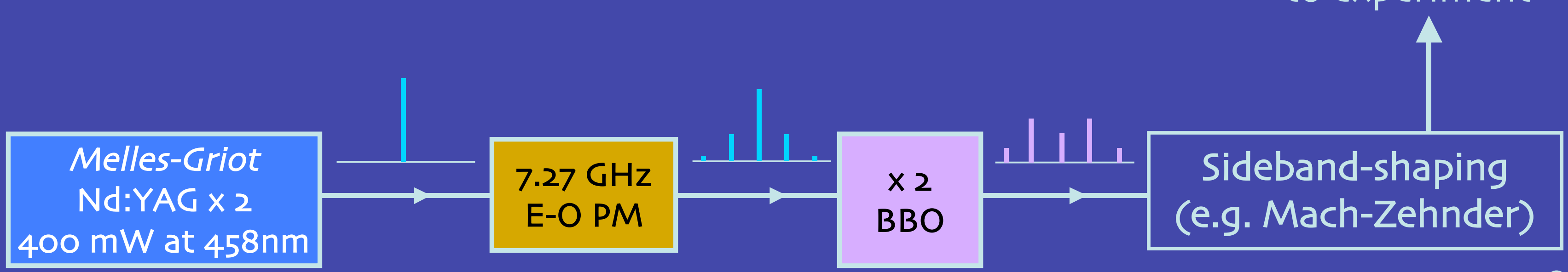
Ramsey fringes using microwaves



Single qubit rotations via stimulated Raman transitions

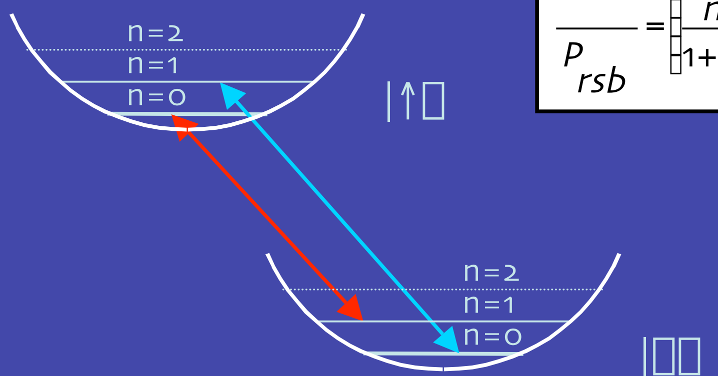


Solid state Raman beam source at 229 nm

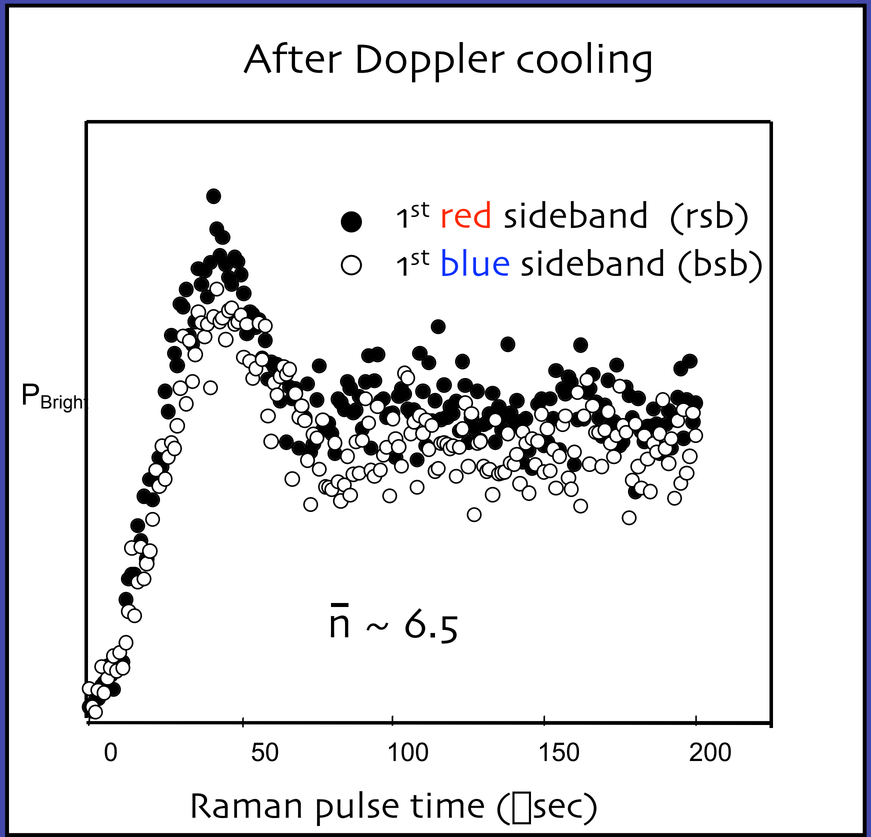


Ion temperature measurement

In counter-propagating Raman beam geometry, strengths of motional sidebands depend on ion's temperature



$$\frac{P_{bsb}}{P_{rsb}} = \left(\frac{\bar{n}}{1+\bar{n}}\right)$$



Current work:

- Sisyphus cooling to near-ground state
- Reducing Raman laser intensity noise and phase noise
- Mølmer-Sørensen entanglement with few ions

Scalability issues

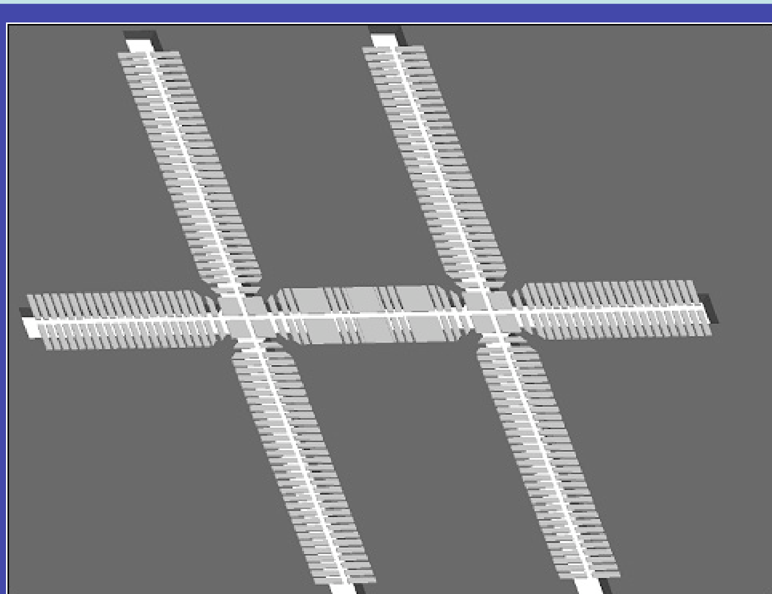
- Original Cirac-Zoller gate:
  - size determined by number of ions in a single trap - can be scaled up by making larger trap
  - ***but*** : ground-state cooling of motion is required - very hard for large ion crystals!
- Two-ion gates (Mølmer-Sørensen, “push”, “ultrafast”, ...):
  - only work for a pair of ions
  - ***no*** ground-state cooling requirement
  - could be scaled by creating arrays of interconnected traps, each containing one ion qubit

Large-scale ion trap quantum computer architectures

ion traps

"conventional"

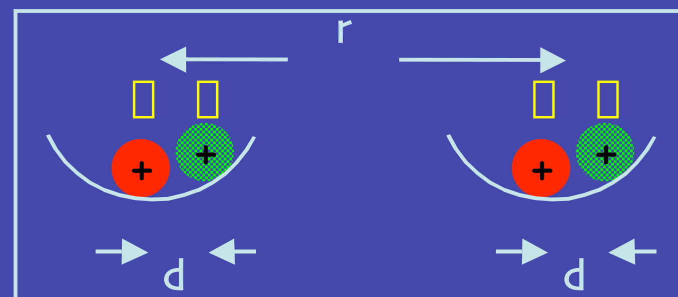
connecting multiple traps, ion shuttling between storage regions and pairwise entanglement areas

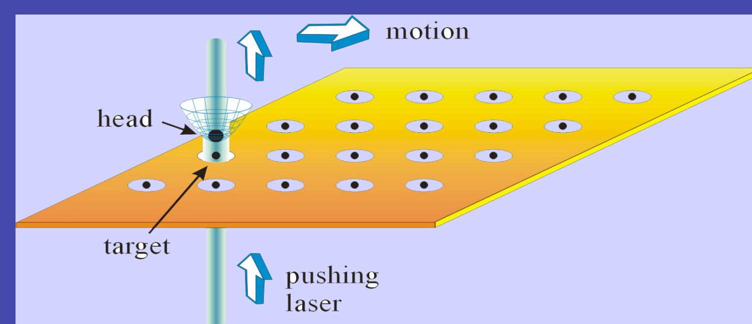


D. Kielpinski, C. Monroe, D. Wineland, *Nature* **417**, 709 (2002)

strong coupling

applying spin-dependent force to entangle ion pairs

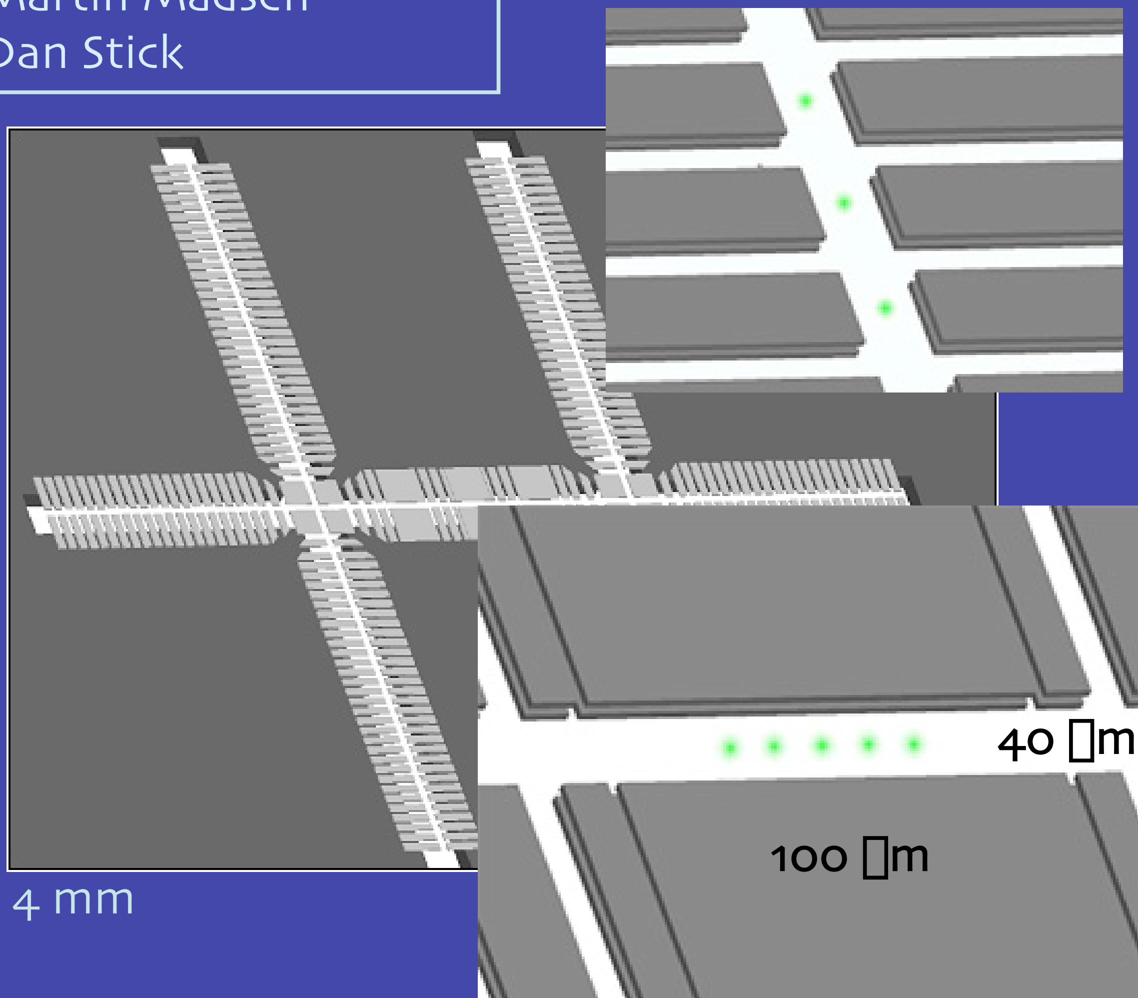




Cirac and Zoller, *Nature* **404**, 579 (2000)

Microfabricated traps and trap arrays

Winfried Hensinger
Martin Madsen
Dan Stick

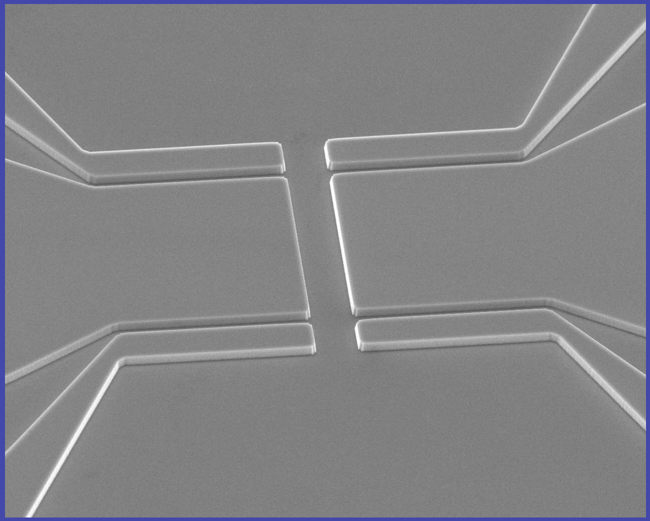


4 mm

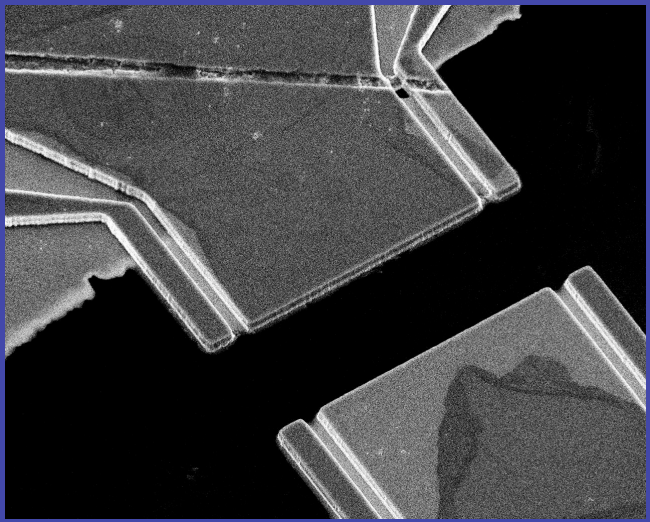
- qubit ions stored in individual traps
- ions shuttled between traps using static electric fields

- ~40 micron transverse size
- good control of ions' positions with static voltage electrodes

Microfabricated traps - SEM pictures



Electrode structure created on the substrate



Substrate etched away underneath the trap electrodes; cantilevers formed

Speeding up trapped ion quantum processor

- Gate speed:

  Phonon-mediated gates (CZ and MS gates):

  - collective motion of ions used as data bus – gate speed must be much slower than ω_{Trap} ~ 1 MHz

  "Push" gate:

  - entanglement through *direct* Coulomb interaction so can be fast

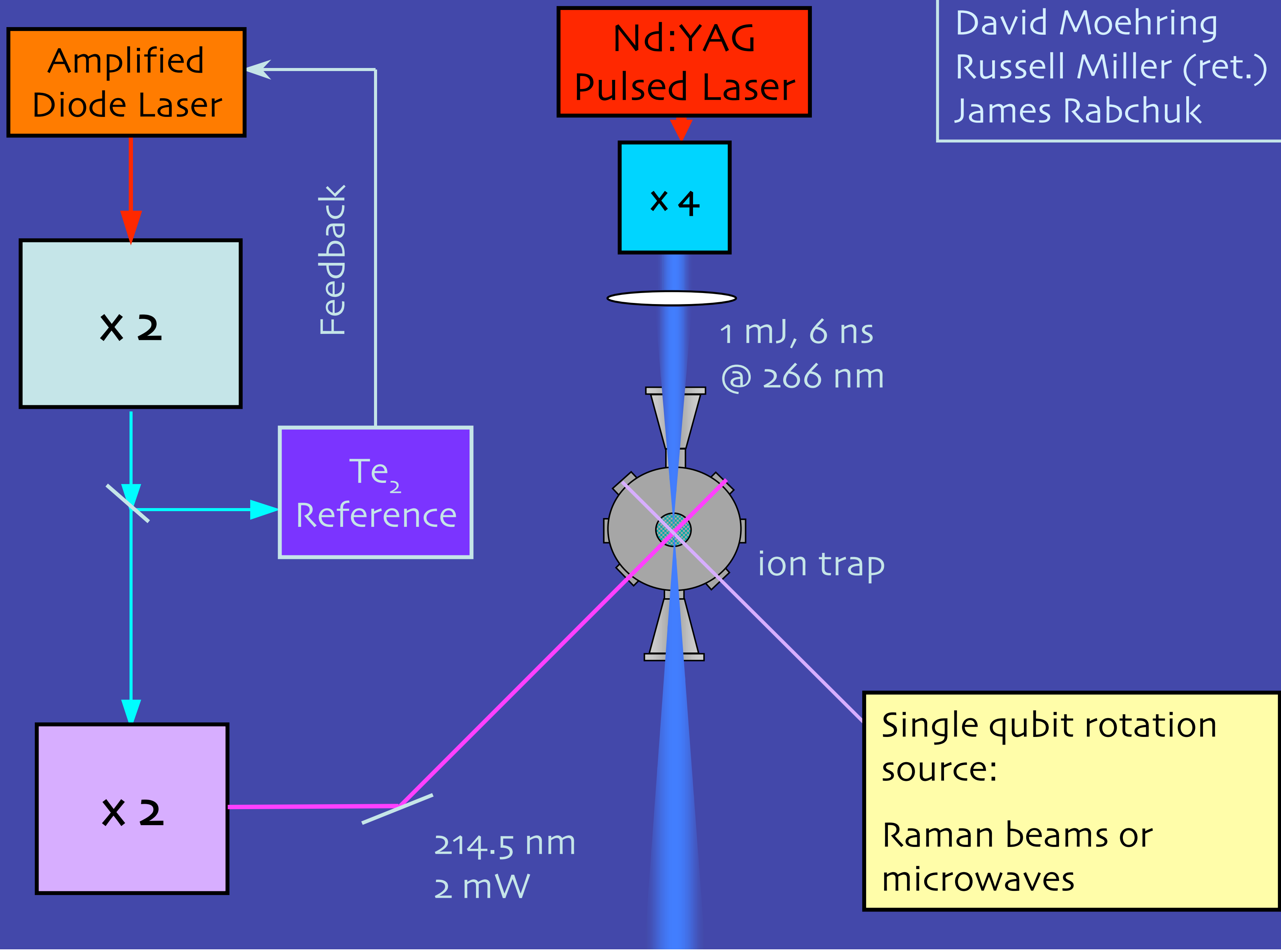
  "Ultrafast" gate:

  - an autobahn!

    (arXiv:quant-ph/0306006)

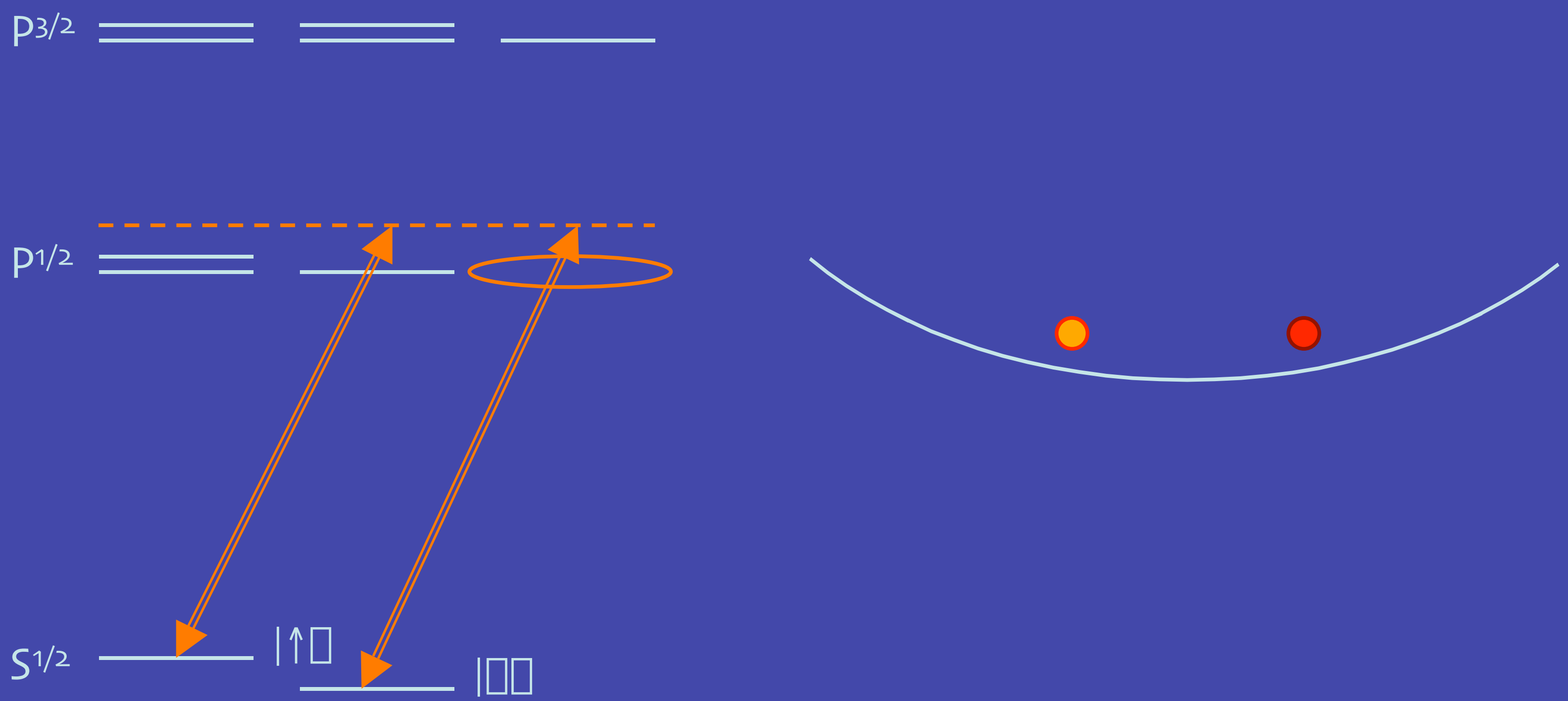
Pulsed laser experiment

Boris Blinov
David Moehring
Russell Miller (ret.)
James Rabchuk



Phase “push” gate with high-power laser pulses

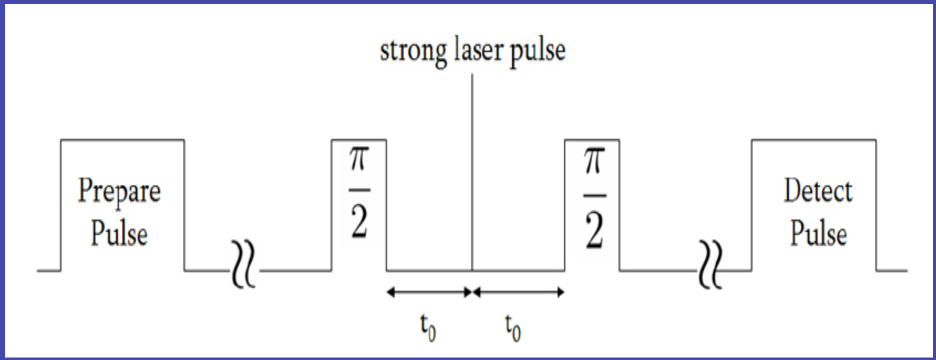
- Ions prepared in Lamb-Dicke limit
- Spin-dependent dipole force (edge of a Gaussian beam waist or a standing wave) is applied to both ions
- The $|\uparrow\rangle$ part of ion is displaced; extra phase is acquired if both ions were in state $|\uparrow\rangle$
- Ions brought back to rest

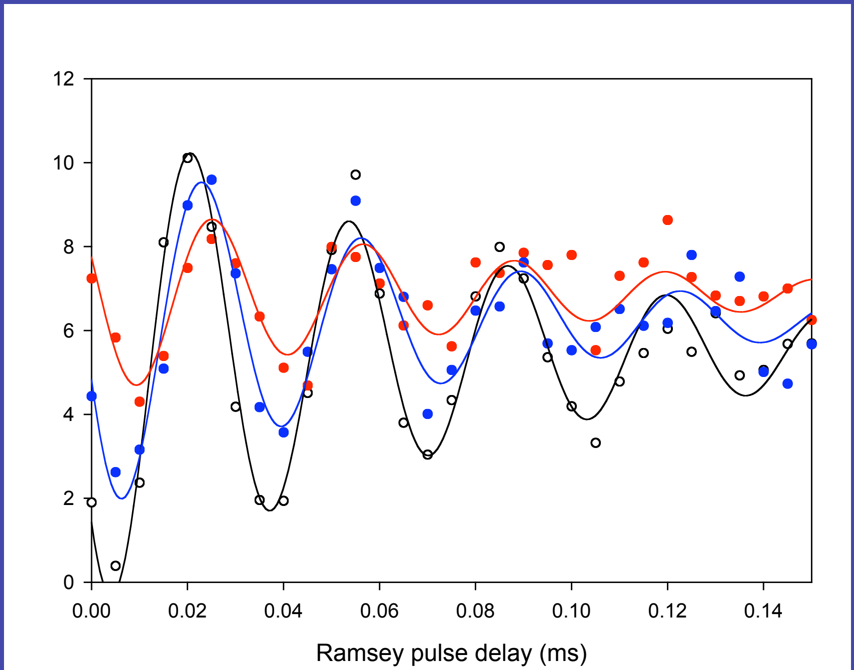


Cirac and Zoller, *Nature* **404**, 579 (2000)

Laser pulses interacting with ions

Strong laser pulses cause very large AC Stark shifts which can be detected.

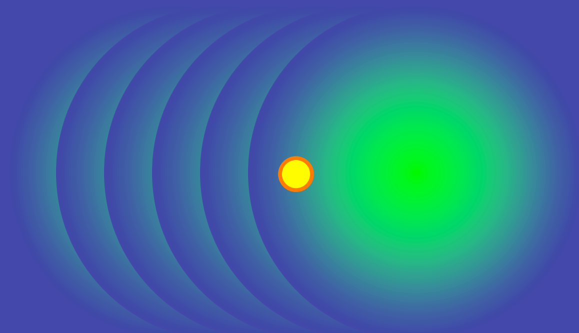


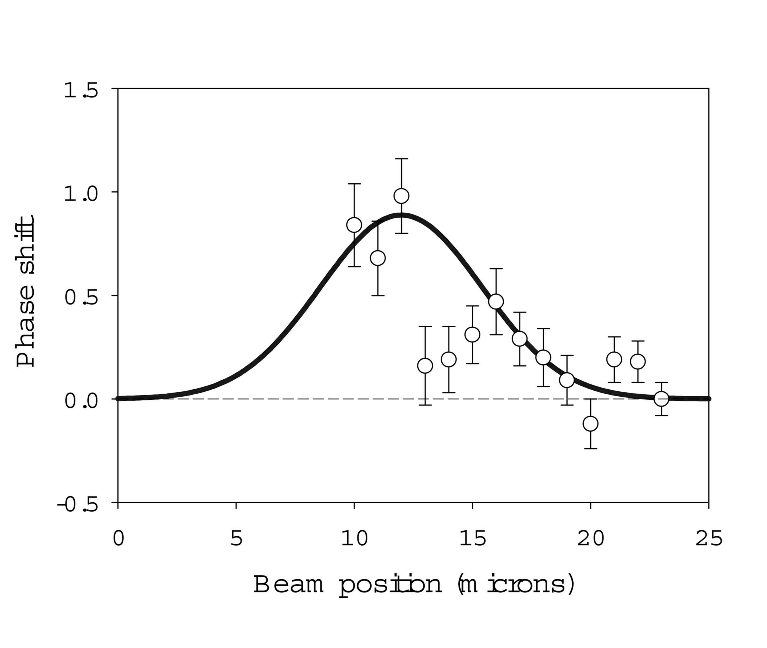


However, pulse-to-pulse noise washes off the Ramsey fringe contrast. Only low intensity pulses can be measured.

Laser beam profile extracted from AC Stark shift data

Measure AC Stark shift while scanning the pulsed laser beam across the ion

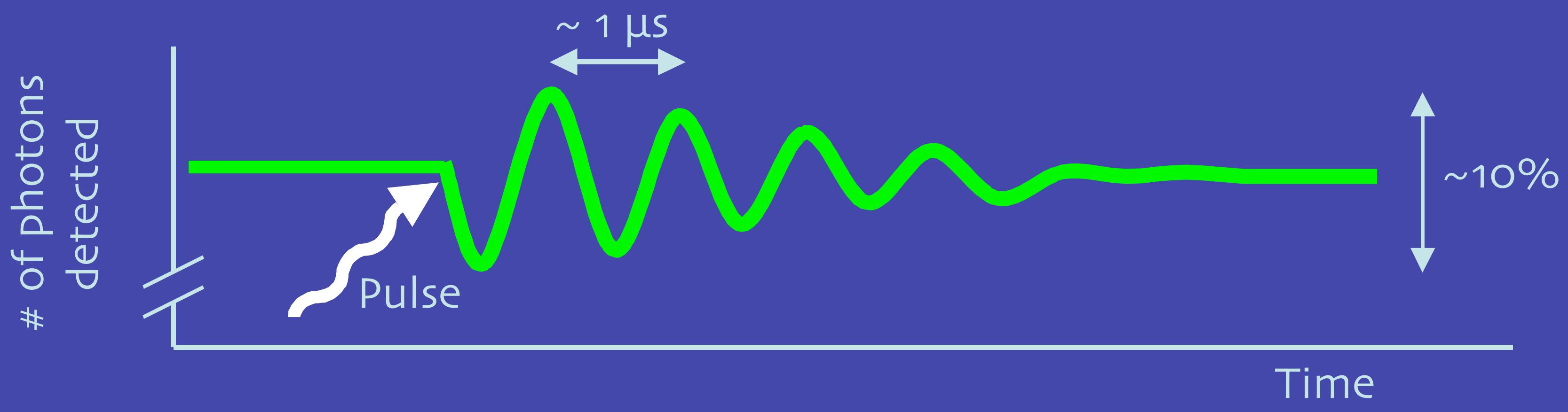




A lot of fine structure in the beam intensity profile (expected - beam is not TEM_{00})

Detecting pushing of ions

Knowing the beam waist profile, can place the ion on high slope of laser intensity to “kick” the ion with dipole force. Ion fluorescence oscillates with secular frequency due to Doppler shifts



Future work:

- shuttling of ions between traps using laser pulses
- “ultrafast” gate

Conclusions and outlook

- Trapped ions hold a great promise for practical quantum computation
- Large arrays of ion traps provide suitable environment for qubit storage and manipulation
- Micro-traps would allow faster quantum logic, as well as capability of coupling the ions to optical photons
- Novel methods of trapped-ion entanglement using strong pulsed laser force are studied to increase the gate speeds